CONSTRAINING THE FLUX OF IMPACTORS POSTDATING HEAVY BOMBARDMENT USING U-PB AGES OF IMPACT GLASSES.

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Introduction: Spherules of glass varying in size from a few micrometres to a few millimetres are common in the lunar regolith. While some of these glass beads are products of pyroclastic fire fountains others originate as impact melt ejected from the target that breaks into small droplets and solidifies as spherical particles while raining back to the lunar surface. These glasses preserve information about the chemical composition of the target and often contain sufficient amount of radioactive nuclides such as ^{40}K to enable ^{40}Ar-^{39}Ar dating of individual beads. Studies measuring the age of glass beads have been used in attempts to establish variations in the flux of impactors hitting the Moon, particularly during the period that postdates the formation of major impact basins [1,2]. These studies proposed a possibility of spike in the impact flux about 800 Ma [2] and over the last 400 Ma [1]. More recently U-Th-Pb isotopic systems have been also utilized to determine the age of impact glasses from the Apollo 17 regolith [3].

Our aim is to extend the application of the U-Pb system in impact glasses to spherules isolated from Apollo 14 soil 14163 in an attempt to further investigate the applicability of this isotopic system to the chronology of impact glass beads and gain additional information on the impact flux in the immer Solar system.

Analytical techniques: 145 impact glasses have been selected, using criteria described by Delano et al. [4], from the population of spherules present in the Apollo 14 soil sample 14163. Major elements compositions of these beads have been determined using a wavelength-dispersive electron microprobe at the Centre for Microscopy, Characterization and Analysis (CMCA) at the University of Western Australia. U-Pb ages of the glasses containing more than 0.025 ppm of total Pb have been analysed using a Cameca IMS1280 ion probe located at the Swedish Museum of Natural History in Stockholm (NordSIMS facility), while trace elements and U-Th-Pb chemical ages of all beads have been determined using laser ablation ICPMS with a Lamda Physik Compex 110i excimer laser coupled to an Agilent 7500 quadrupole ICPMS at the Australian National University.

Results: Impact glasses commonly show a broad and continuous range of chemical compositions that are consistent with mixing of diverse components either within the lunar regolith or during the impact process.

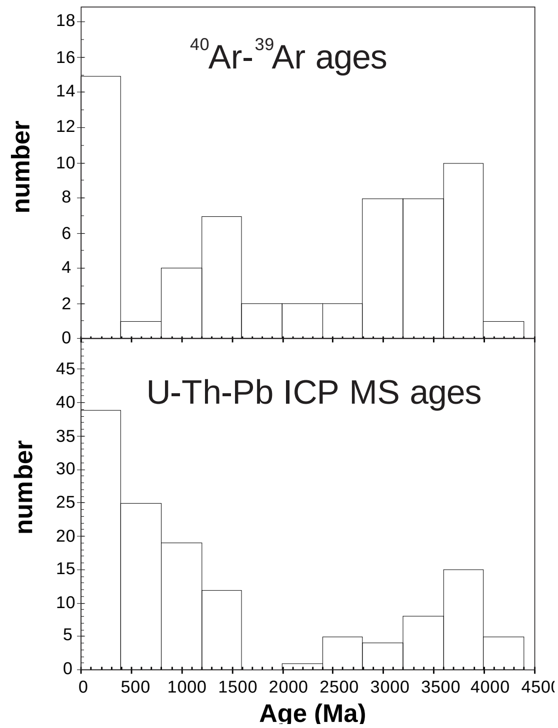

Figure 1. ^{40}Ar-^{39}Ar (155 glasses, data from Culler et al. [1]) and U-Th-Pb chemical (145 glasses) age distribution patterns for the glass beads from the Apollo 14 soil sample 14163.

Analogous to the variations observed in lunar rocks and regoliths, the range of compositions in lunar impact glasses can be broadly described in terms of their correlated variations in Al_2O_3, FeO_t (total Fe expressed as FeO) and K_2O, reflecting feldspathic and mafic components in the pre-impact targets, plus a variable contribution of incompatible-elements associated with KREEP [3]. Chemical compositions of 145 impact glass beads from the sample 14163 are consistent with the variable contribution of these three components. Several compositional groups of glass can be identified among the analyzed glasses which correspond to likely target materials available on the Moon. These potential target rocks include mare basalts, Mg-suite rocks and feldspatic rocks (with low concentrateons of incompatible elements). In addition significant proportion of glasses have intermediate compositions indicating the contribution of multiple components and suggesting a regolith origin. Finally a number of beads have experienced a significant loss of volatile elements, including a noticeable depletion in SiO_2, and can be classified as HASP glasses described by [5].

U-Th-Pb chemical ages determined for 145 glass beads from sample 14163 using ICPMS show distribution (Fig.1) similar to that based on ^{40}Ar-^{39}Ar data obtained for the same sample by Culler et al. [1]. One possible exception is presence of significant number of U-Th-Pb ages around 500 Ma. However, comparison of U-Th-Pb and $^{207}Pb/^{206}Pb$ ages obtained for the same spherules indicates that a significant proportion of analysed glasses are discordant (Fig.2)

All beads with the U-Th-Pb chemical ages younger than ~300 Ma are discordant indicating a recent impact that has triggered incomplete Pb loss from the much older glass beads. Similar conclusion can be made for a number of glass beads with the U-Th-Pb around 500 Ma.

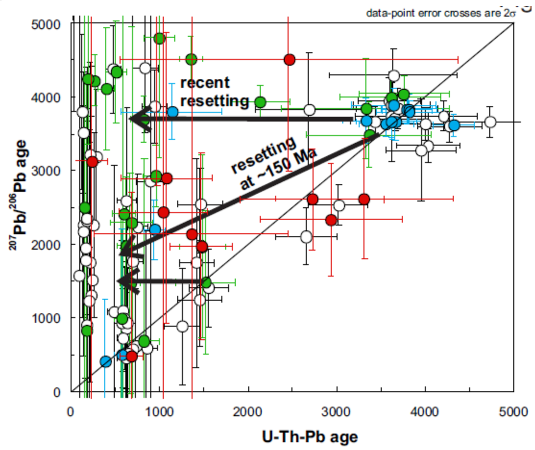

Figure 2. U-Th-Pb vs. $^{207}Pb/^{206}Pb$ ICP MS ages of some analysed glass beads. Colours represent different chmical composition of the target materials (green: mare basalts; light blue: Mg-suite rocks , red: feldspatic, white: local regolith).

Consequently two relatively young events at ~500 and <300 Ma that resulted in partial resetting of U-Pb systems in the glasses of different compositions can be recognized from the discordia trends. The upper concordia intercepts of these trends, though very imprecise, indicate formation ages of these beads The true formation ages can be only determined for the glasses showing undisturbed U-Pb systems.

These ages indicate that the proportion of regolith in the target materials is larger in the younger beads. The change in target materials can be a result of both growth of regolith cover with time and a diminishing proportion of larger impacts capable of penetrating deeper than the surficial layer of regolith. The concordant ages also suggest that primary mare basalt and Mg-suite targets are mostly restricted to the 3.8-3.6 Ga time interval, although some are significantly modified by ~500 and <300 Ma impacts. Feldspatic (high Al) glasses identified in the sample appear to be restricted to a single event at 2498 ±53 Ma, although similar to the basaltic and Mg-suite glasses they have been modified by two young impacts.In general temporal trend can be characterised as primary lithic targets dominating earlier impacts, which are gradually replaced by the increased reworking of previously formed regolith in the later impacts

Implications for the post LHB impact flux: Age groups identified from the study of U-Pb sytems in the glass spherules from soil sample 14163 are shown in Figure 3. Although it is not possible to determine strictly the flux of impactors from this data set, it gives indication of major changesin the flux that occured during the past 3.8 billion years.

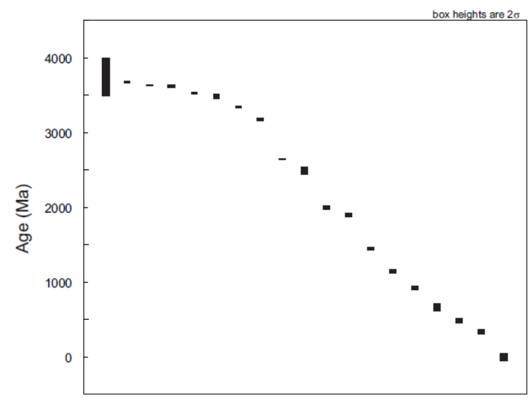

Figure 3. Age groups observed in the population of impact glasses from the sample 14163

The approach makes an assumption that all beads with similar ages originate in the same impact. While probably valid for the beads with similar chemical composition, it is more difficult to justify fully for the mixed populations of glasses. However, partial resetting of U-Pb systems visible in a number of beads suggests that some (especially younger) impacts can reset U-Pb systems in variety of previously formed glasses. A potential pitfall of this approach is that some of the impacts within the narrow time intervals compatible with the analytical errors can be unrecognised and treated as a single impact. Nevertheless plotting all identified age groups determined for the sample 14163 in a sequence (Fig.3) suggests a higher flux prior to ~3.5 Ga, possibly at the extension of the heavy bombardment period, and lower, but lower and relatively constant flux after ~3.0 Ga. This newly obtained U-Pb data appears to contradict the conclusions made on the basis of ^{40}Ar-^{39}Ar analyses of impact glasses.

References: [1] Culler et al (2002) *Science*, 287, 1785-1787; [2] Zellner et al (2009) *Meteoritics & Planet. Sci.*, 44, 839-851; [3] Norman et al. (2012) *AJES*, 59, 291-306; [4] Delano et al. (1996) *Proc. Lunar Sci. Conf. 16th*, D201–D213; [5] Naney M.T. et al. (1976) *Proc. Lunar Sci. Conf. 7th*, 155-184